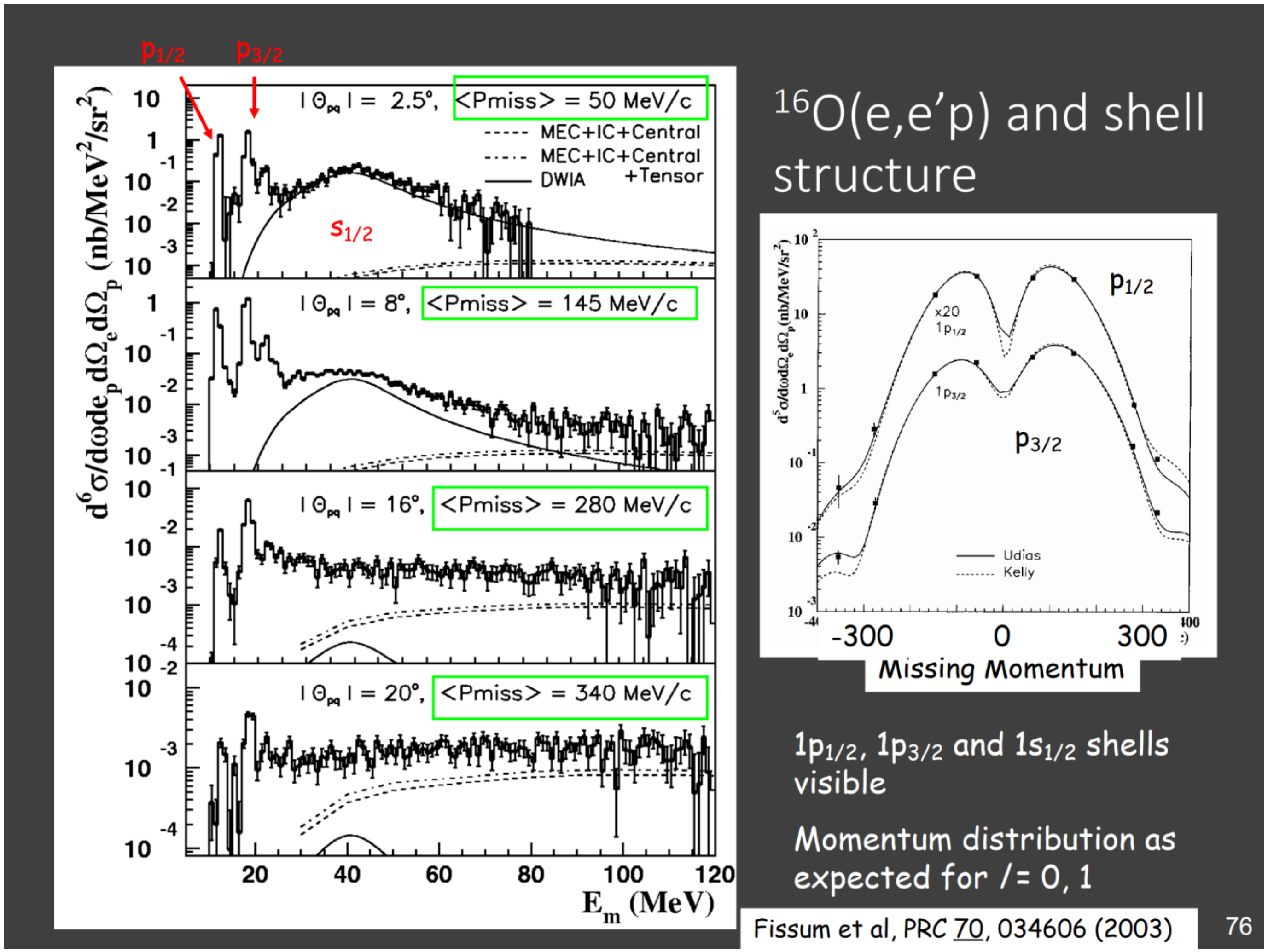
Nuclear structure studies using inverse kinematics experiments

Julian Kahlbow

Photonuclear Reactions Workshop
Aug 10, 2024

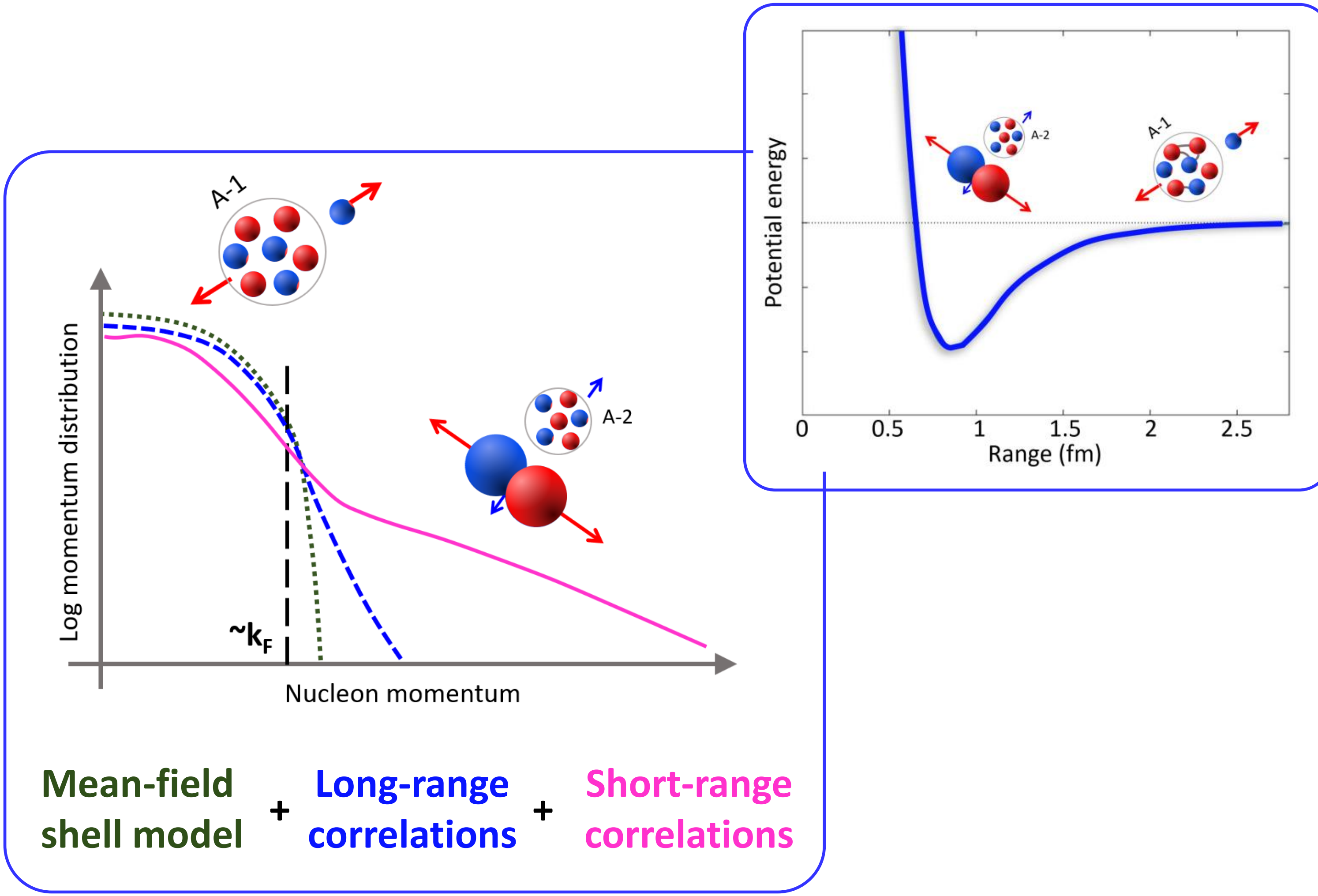
You heard on Wednesday …

Quasielastic scattering = Tool to study nuclear structure



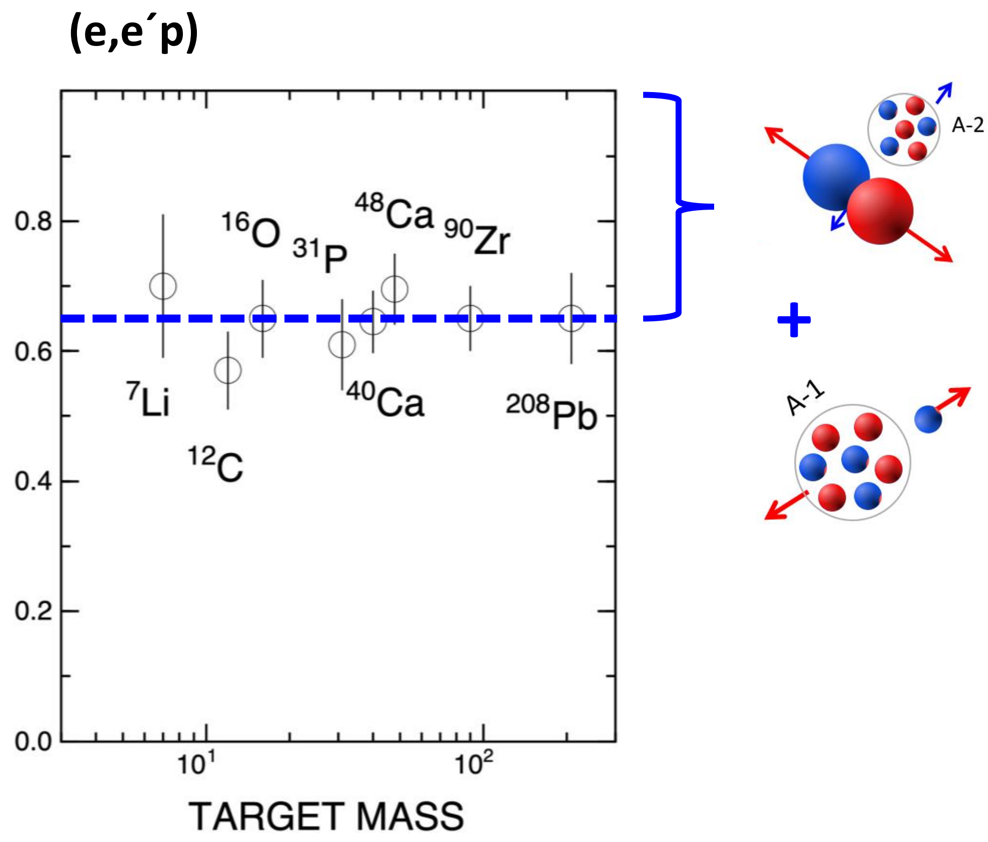
Slide from Or

Nuclear correlations across scales



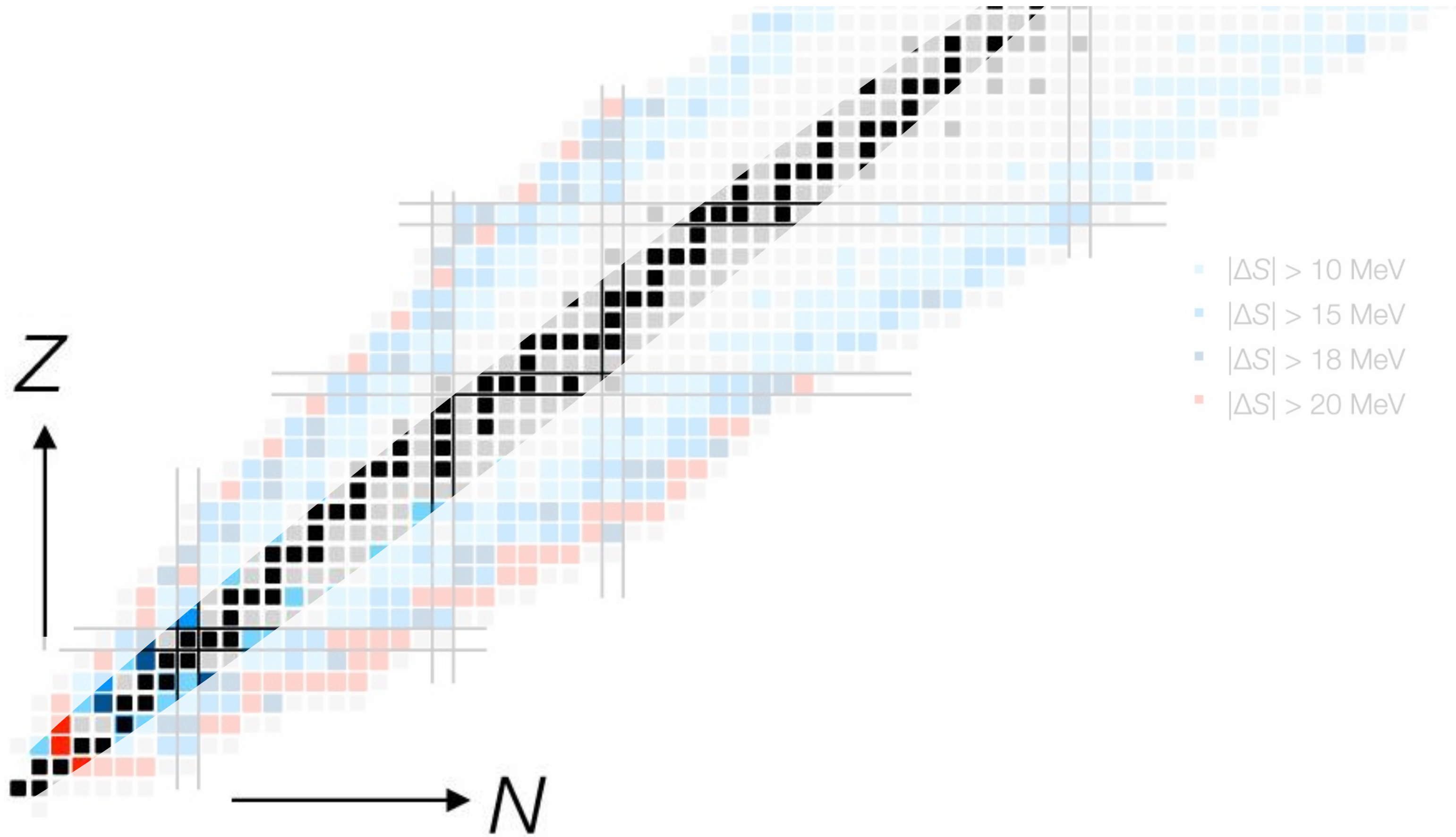
Signs of correlations

Spectroscopic strength
$R_S = \sigma_{exp} / \sigma_{theo}$

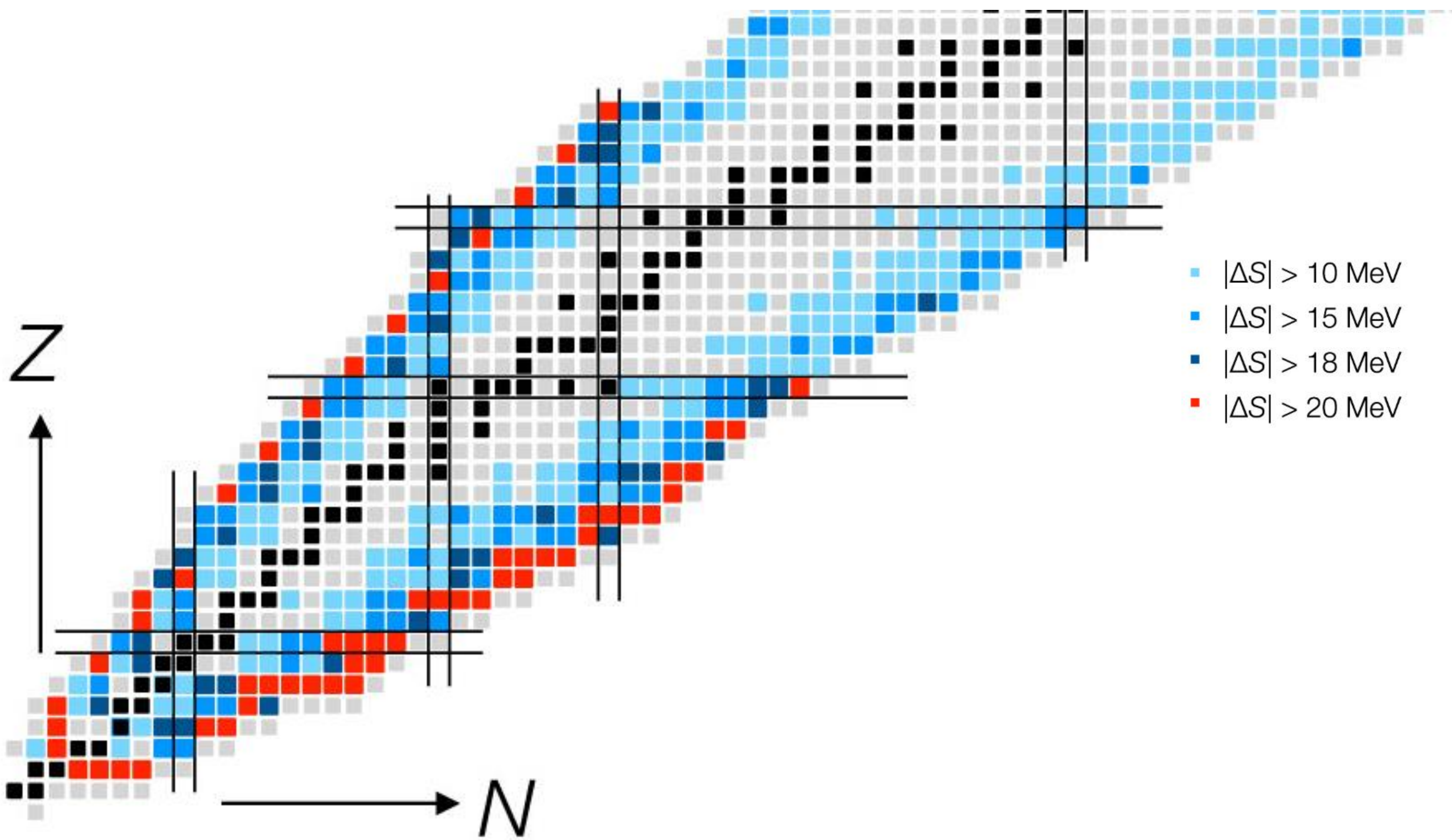


L. Lapikás, NPA 553 (1993).

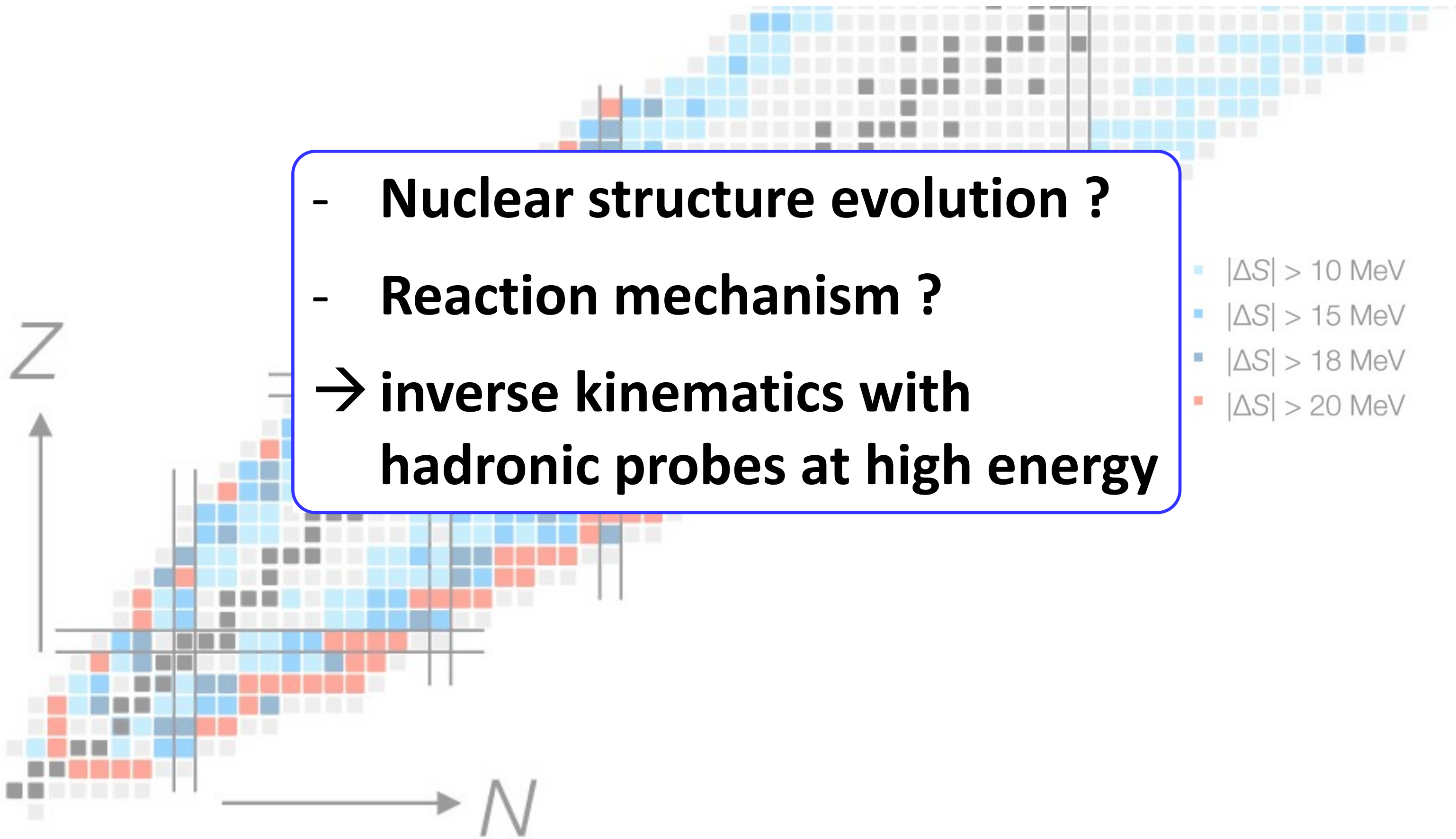
Electron scattering is limited to stable nuclei



Only ~300/3,000 (known) nuclei are stable



Nuclear structure studies in exotic nuclei

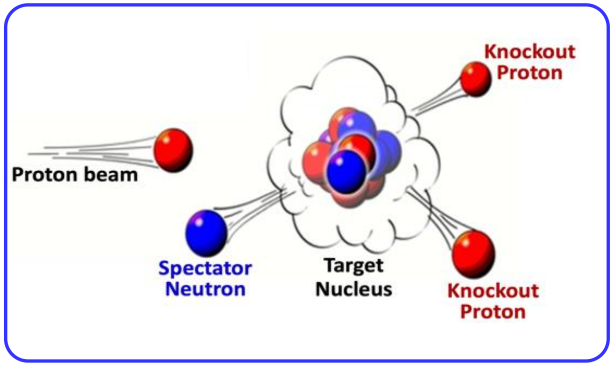


- **Nuclear structure evolution ?**
- **Reaction mechanism ?**

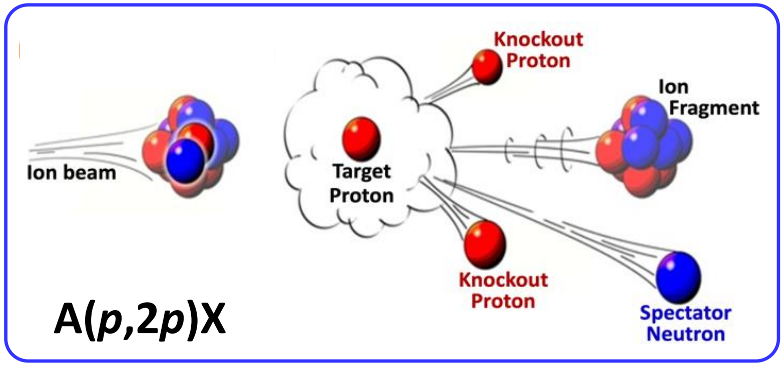
→ inverse kinematics with hadronic probes at high energy

Flipping reaction kinematics provides powerful access to structure!

nuclear target
and p or e$^-$ beam



(radioactive) ion beam
hitting hadronic probe



Flipping reaction kinematics provides powerful access to structure!

nuclear target
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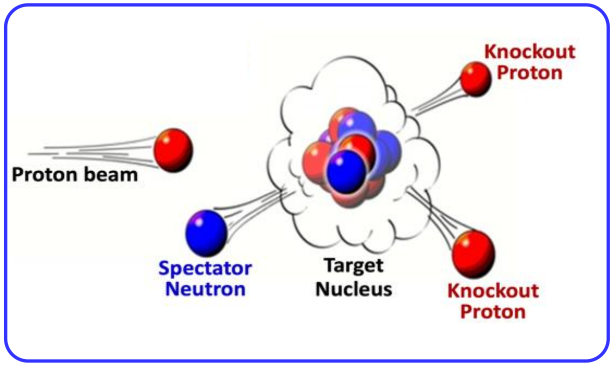

(radioactive) ion beam
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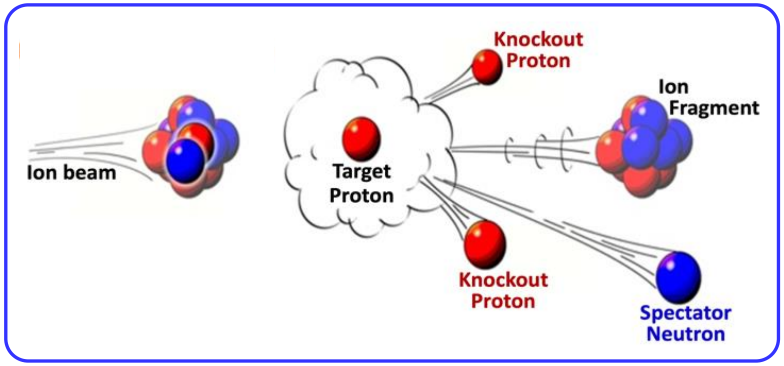
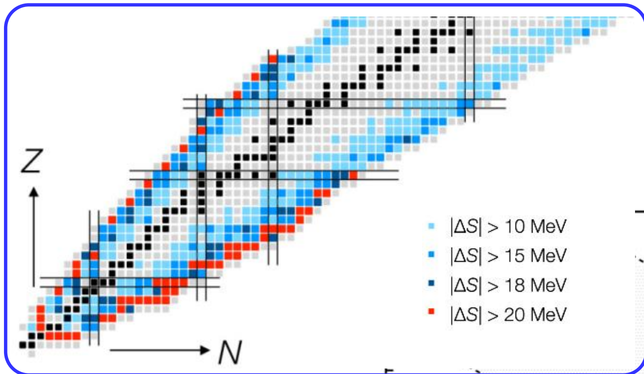
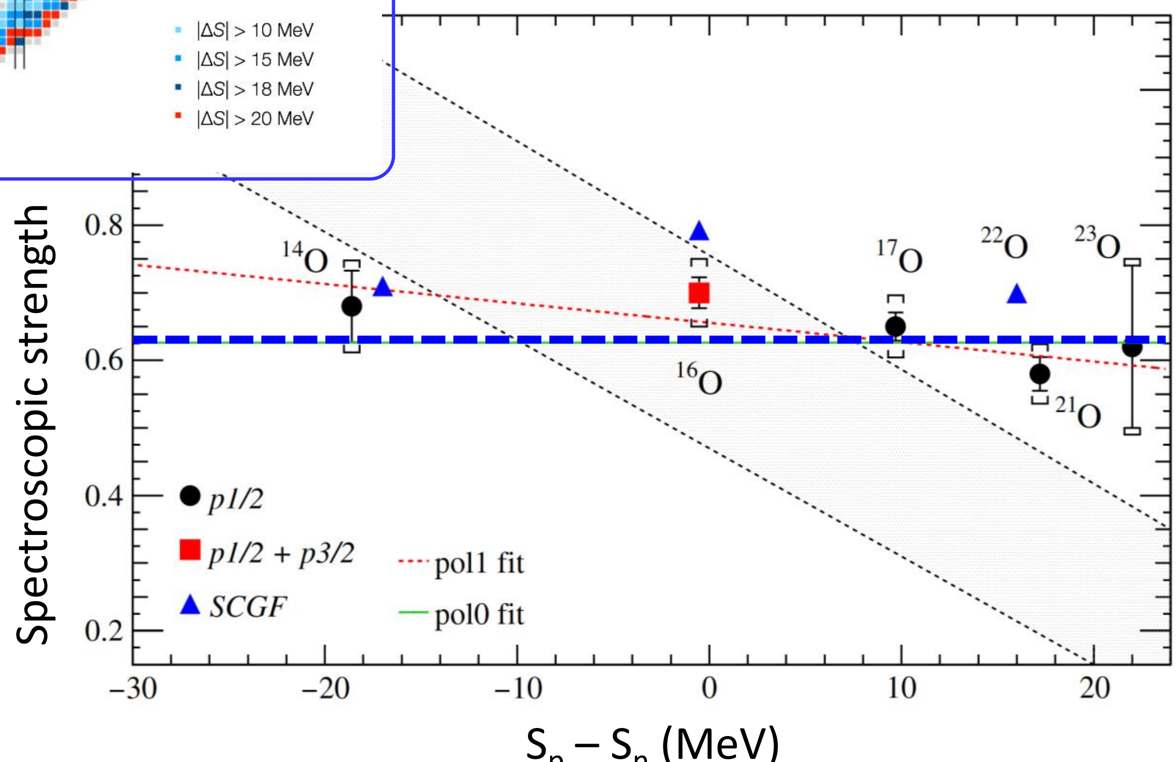


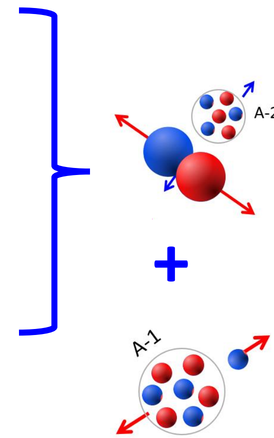
1. **Inverse kinematics: nuclear structure using hadronic probes**
2. **Measure *all* reaction particles**
3. **Final state tagging**

Correlations in exotic nuclei



(p,2p) @ ~400 AMeV

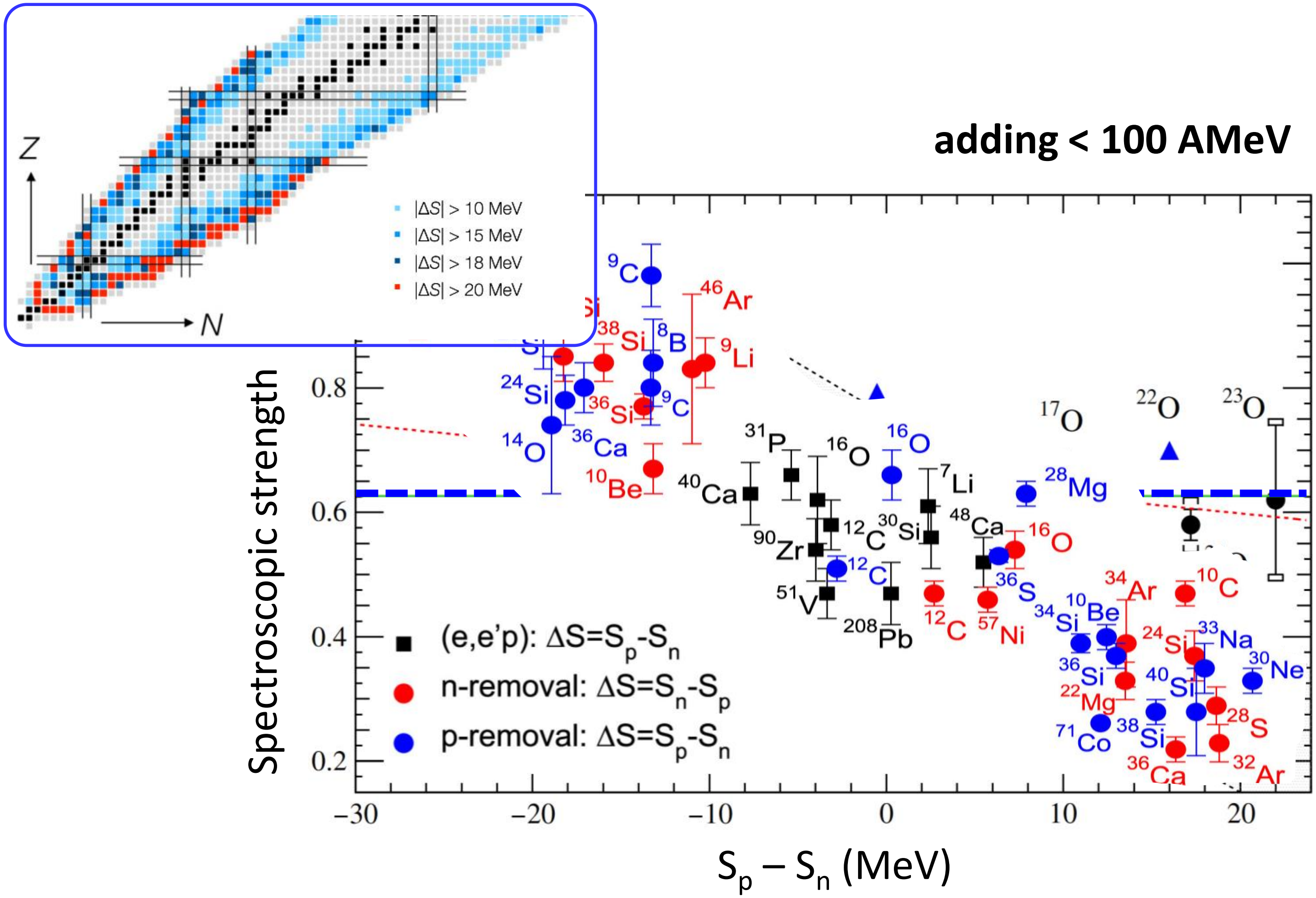




L. Atar et al. (JK), PRL 120 (2018).

Correlations in exotic nuclei

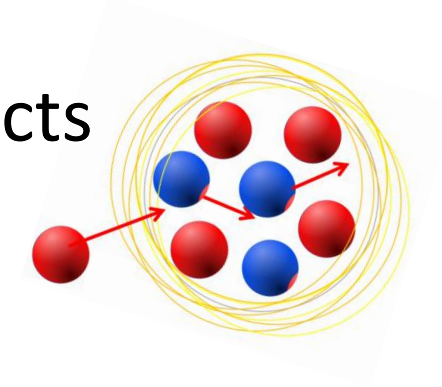
adding < 100 AMeV



?

J.A. Tostevin, A. Gade, PRC 90 (2014).

Disadvantages: Medium effects



Incoming proton and outgoing protons interact with other nucleons
(initial and final state interactions)

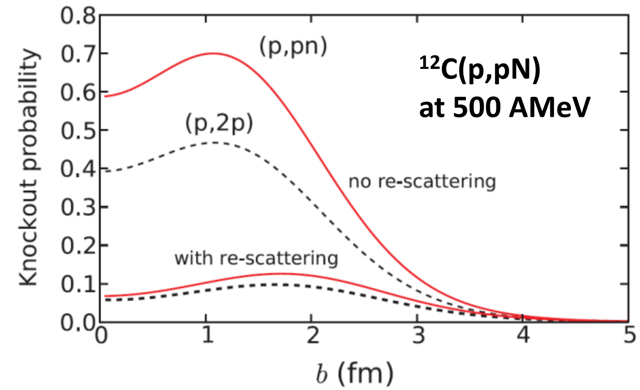
→ disturb initial momentum reconstruction

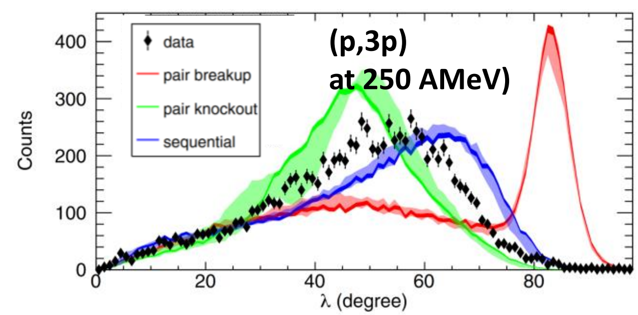
- extra excitations of the nucleus (break fragment apart)

- eject additional particles (pions, …)

→ attenuation/absorption

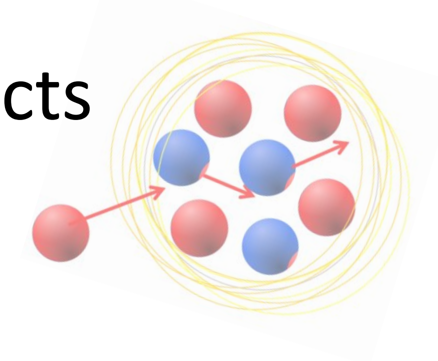
- in-medium effects





T. Aumann, C.A. Bertulani, J. Ryckebusch, PRC 88 (2013).
A. Frotscher et al., PRL 125 (2020).
L. Frankfurt, M. Strikman, M. Zhalov, PLB 503 (2001).
S. Stevens et al., PLB 777 (2018).

Disadvantages: Medium effects



Incoming proton and outgoing protons interact with other nucleons
(initial and final state interactions)

→ disturb initial ... reconstruction

- extra excitation (break fragment apart)

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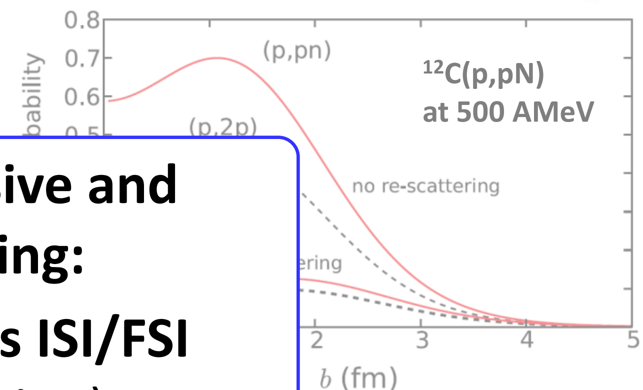
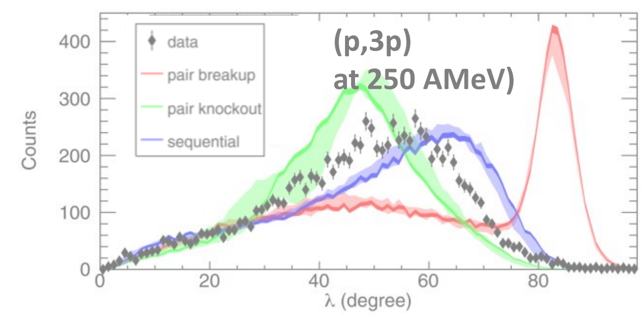
We proof in fully exclusive and high-energy scattering:

Fragment tagging rejects ISI/FSI
(distortion + attenuation)





T. Aumann, C.A. Bertulani, J. Ryckebusch, PRC 88 (2013).
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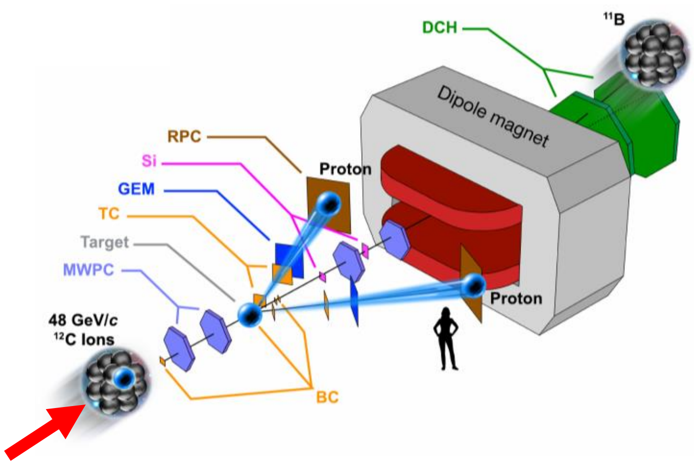
Three experimental campaigns

→ Proton knockout (p,2p) at high energy and large momentum transfer

JINR in 2018 + 2022

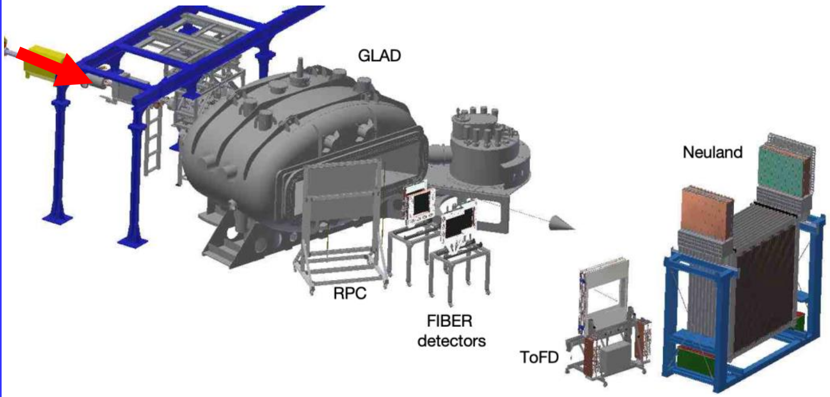
^{12}C @ ~4 GeV/c/u

M. Patsyuk, JK et al., Nat. Phys. 17 (2021).



GSI-FAIR in 2022

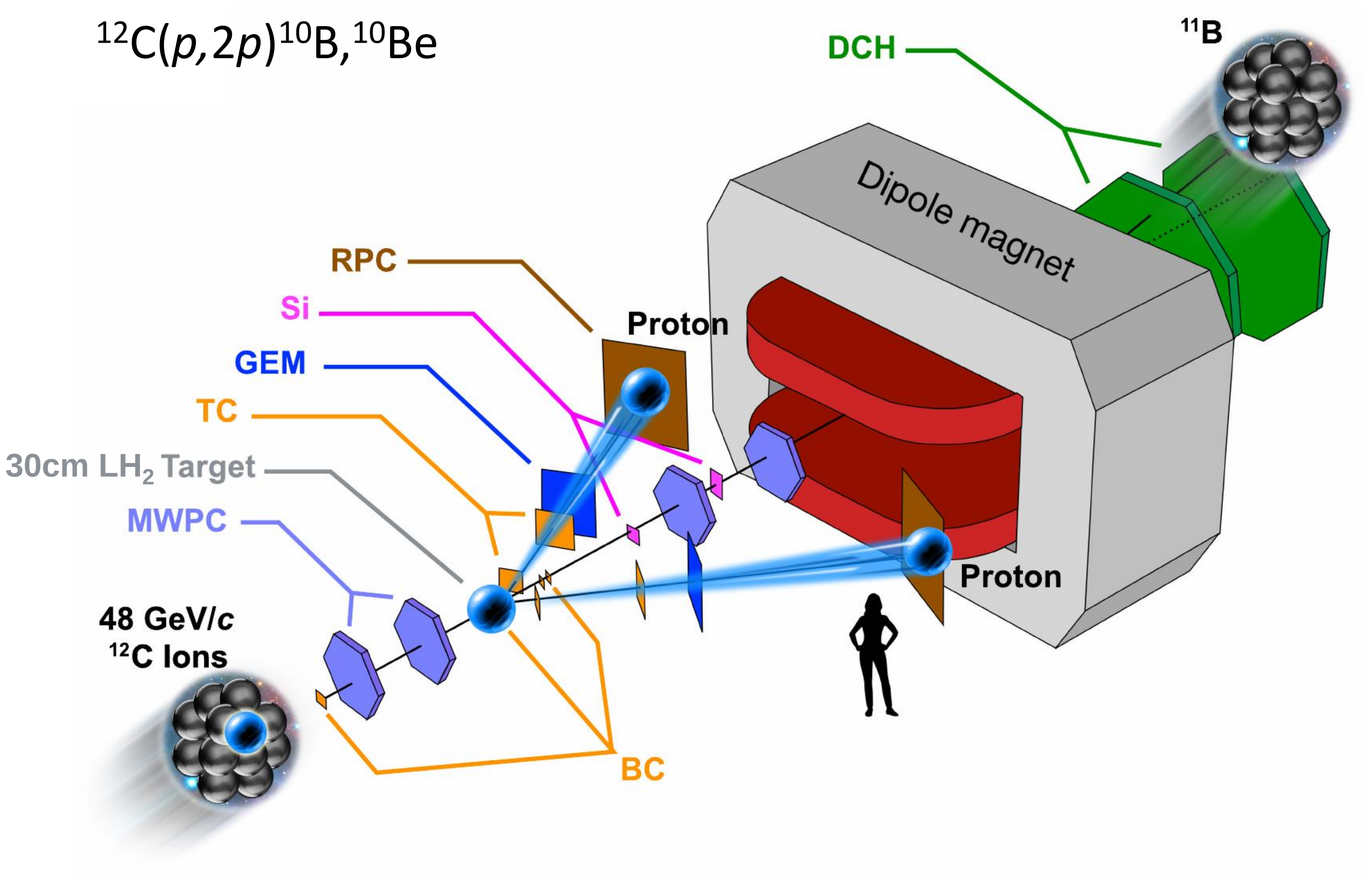
^{12}C & ^{16}C @ 2 GeV/c/u



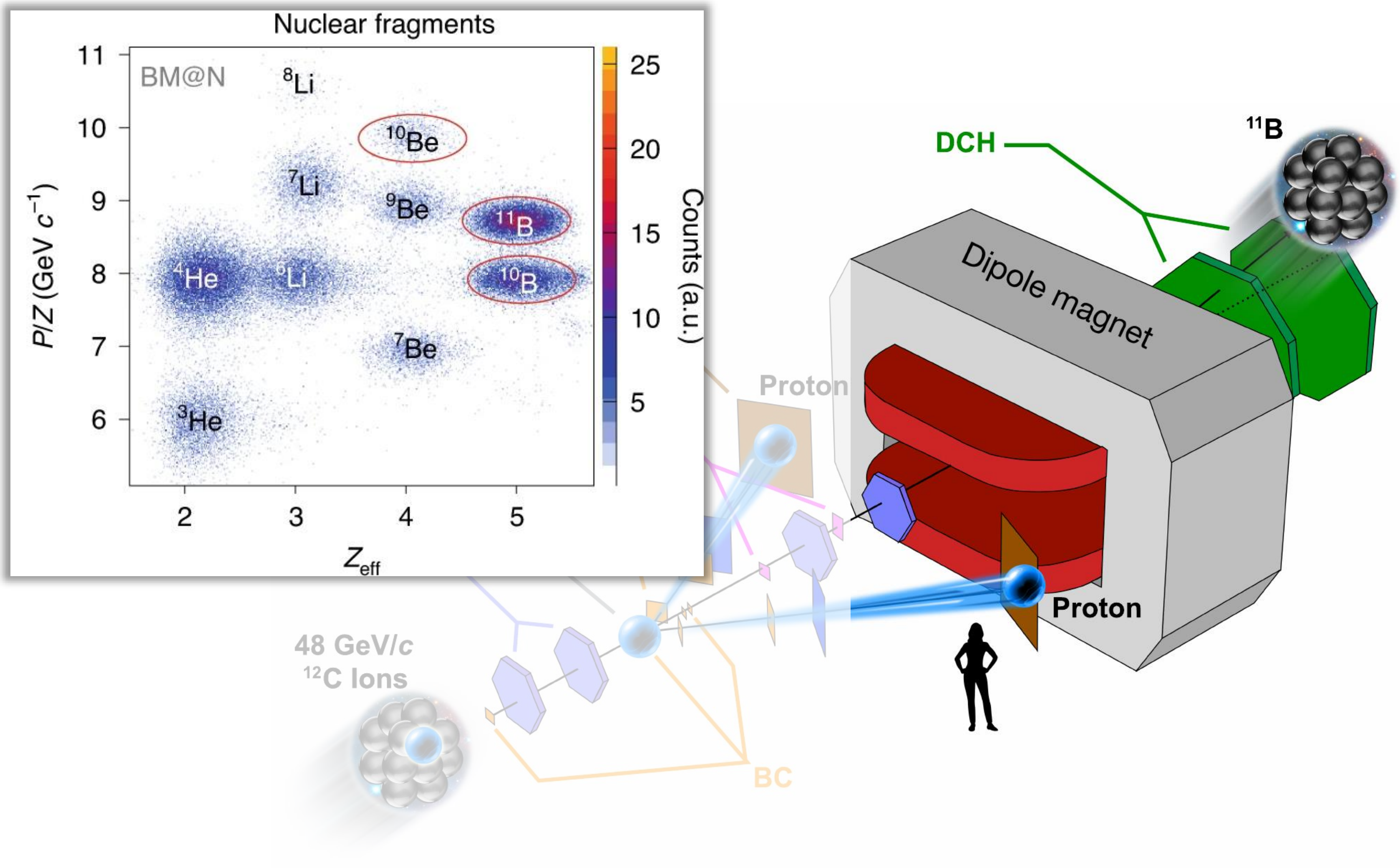
Experiment at JINR

“Mean-field“: $^{12}C(p,2p)^{11}B$

SRC: $^{12}C(p,2p)^{10}B,^{10}Be$



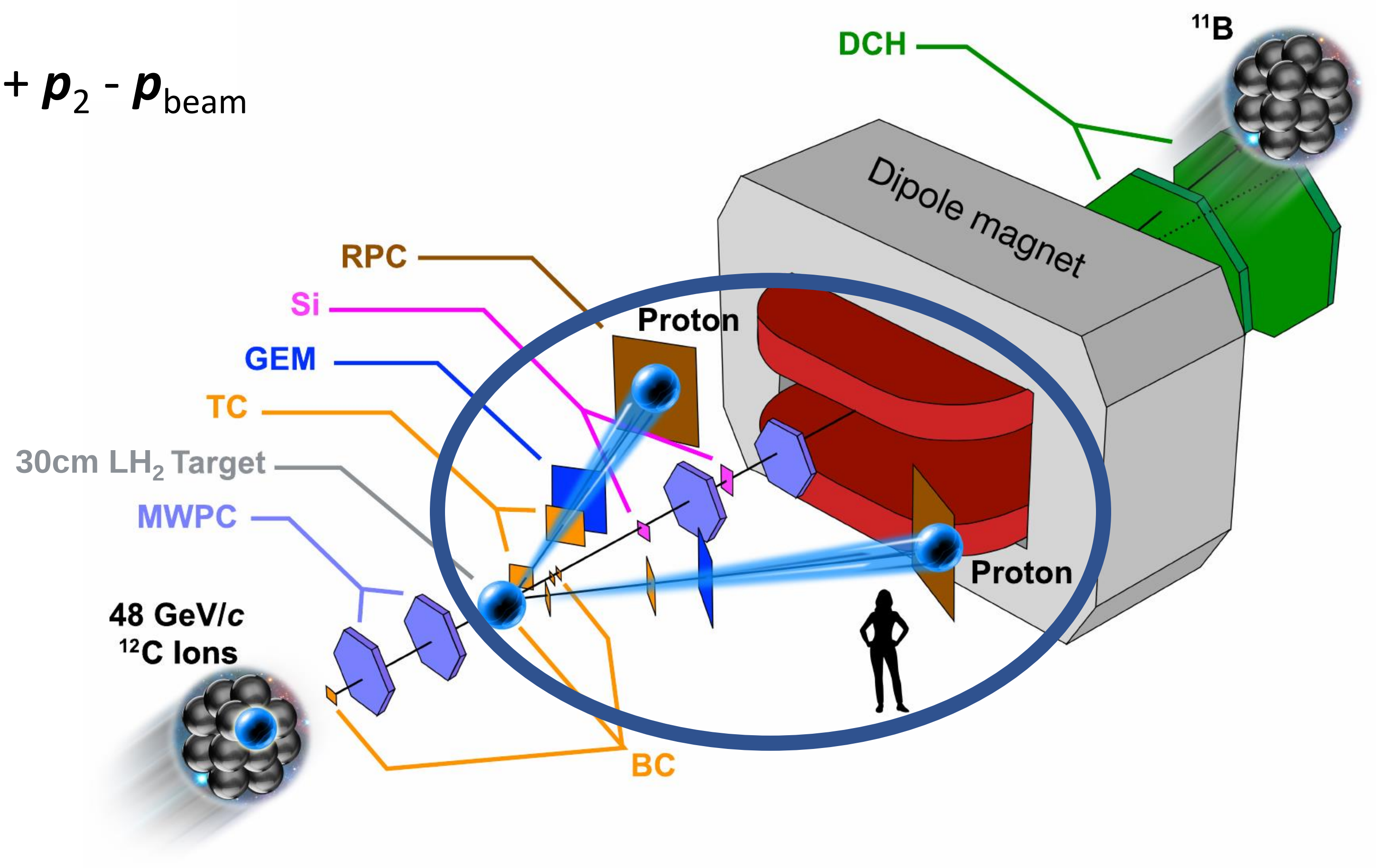
Heavy-fragment identification: post-selection



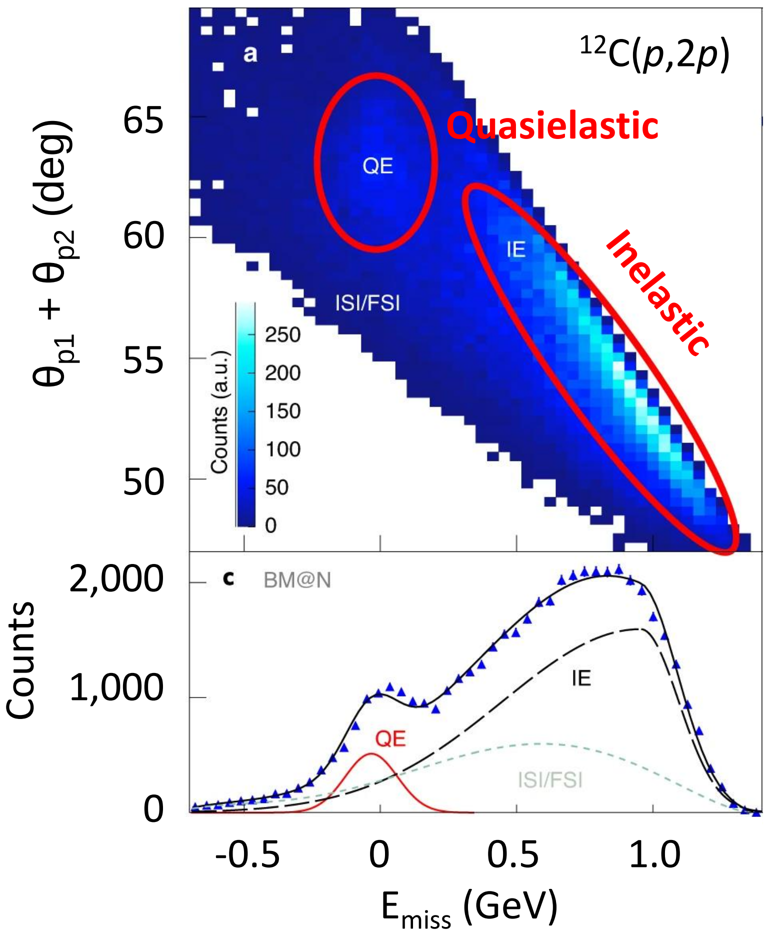
Quasi-free (p,2p) scattering

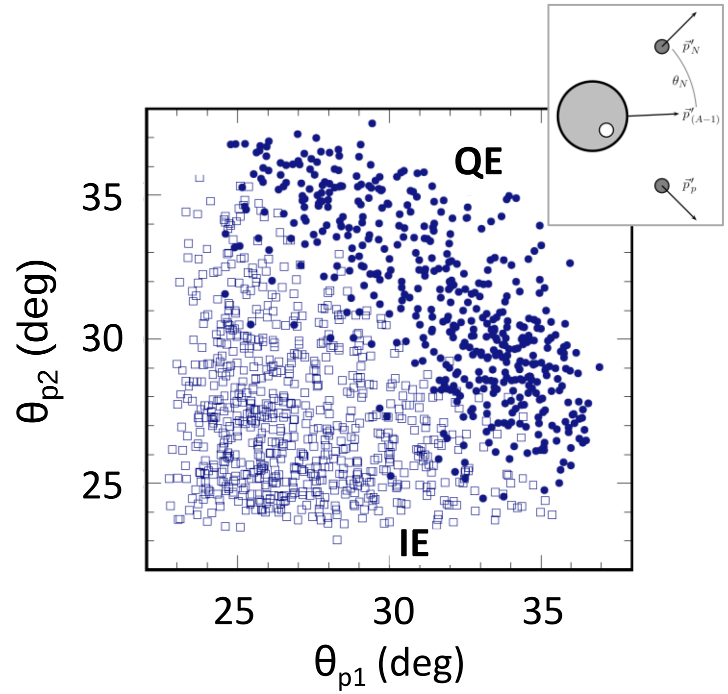
Reconstruct "initial" nucleon momentum from scattered protons

$\boldsymbol{p}_{\text{miss}} = \boldsymbol{p}_1 + \boldsymbol{p}_2 - \boldsymbol{p}_{\text{beam}}$



But: Is QE scattering free of FSI?



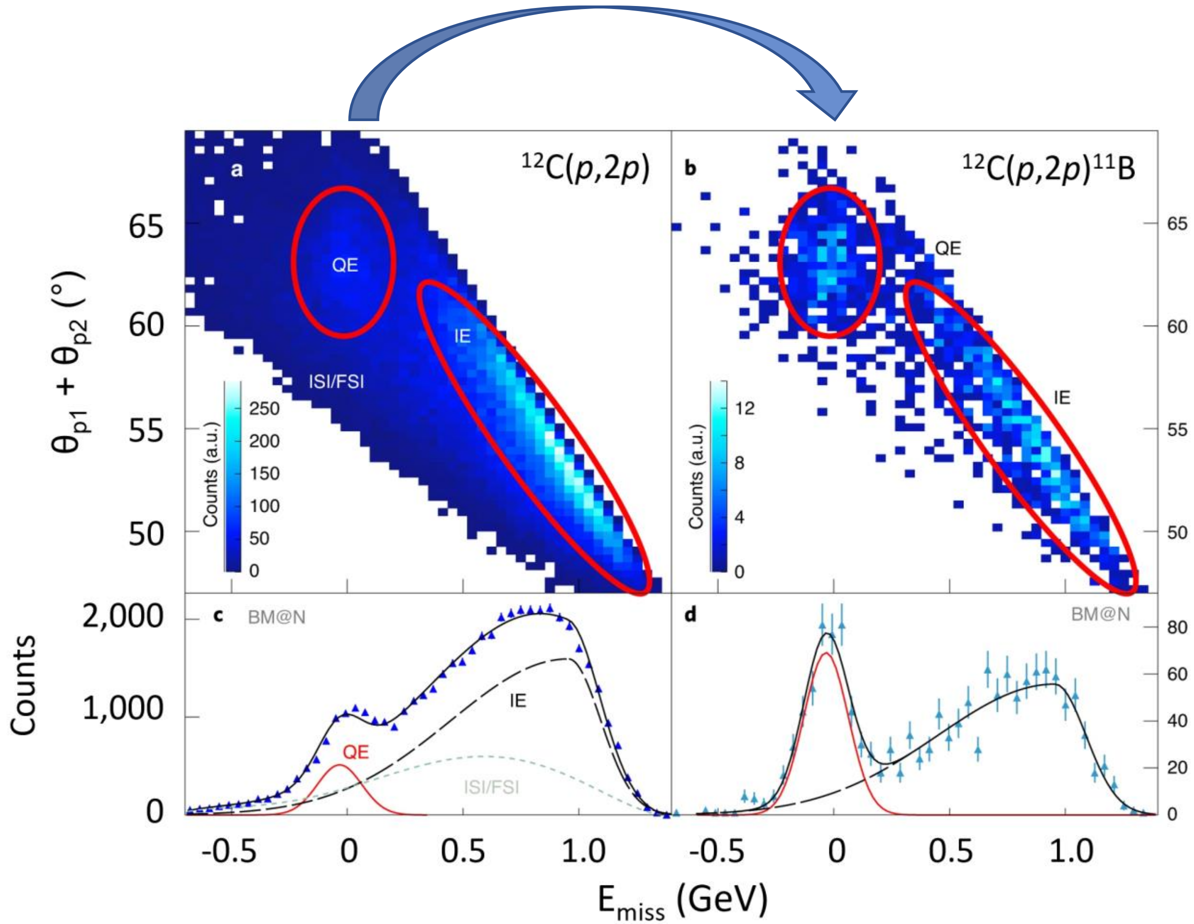


(p,2p) inclusive scattering dominated by inelastic scattering and initial/final state interactions

M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

Reaction mechanism under control

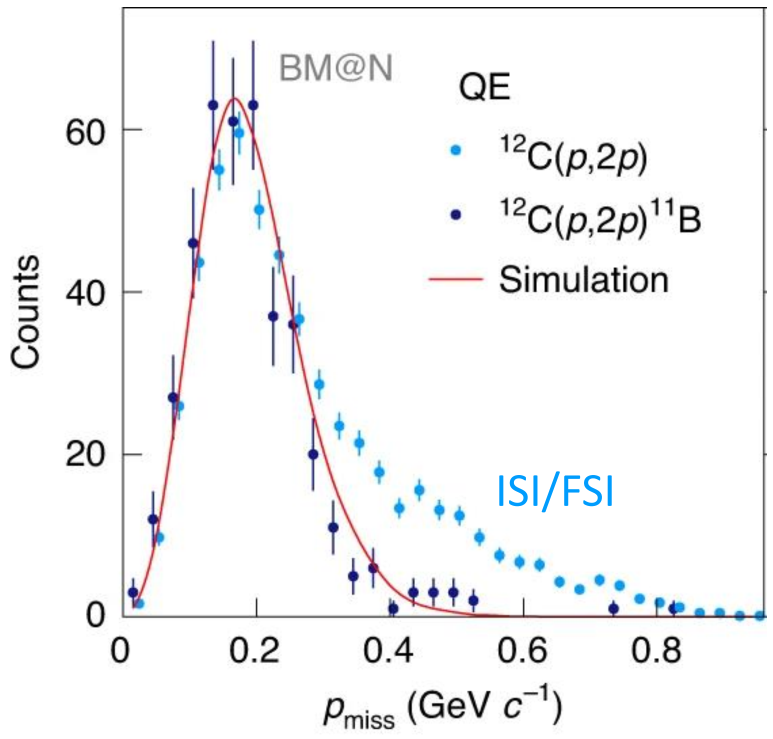
Fragment tagging rejects
initial/final state interactions



M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

Single-step nucleon knockout

→ access ground-state distribution



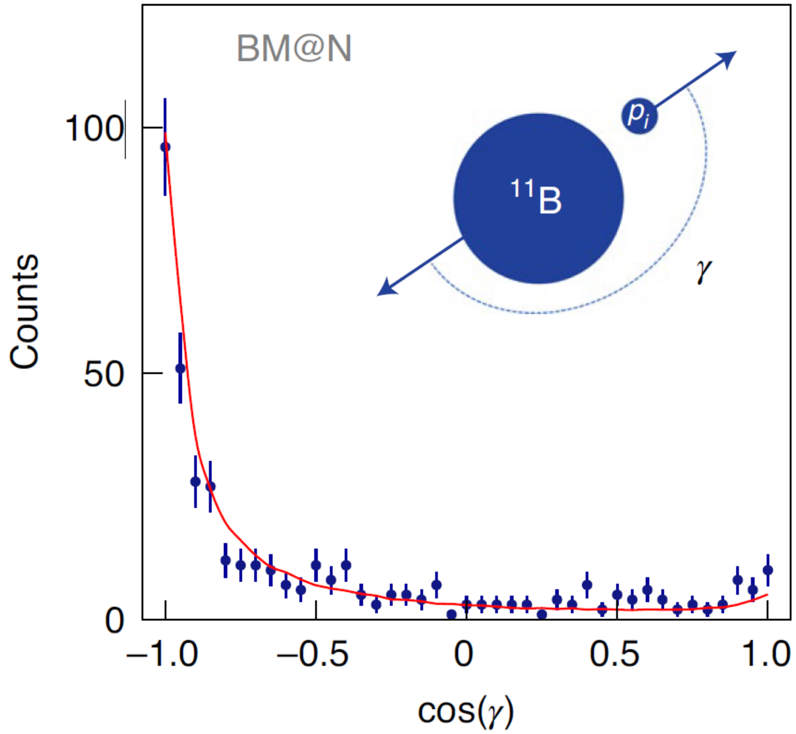
Calculation of QE (*p,2p*) scattering off *p*-shell nucleon in ^{12}C without ISI/FSI

[T. Aumann, C.A. Bertulani, J. Ryckebusch, PRC 88 (2013).]

M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

Fragment-proton correlation

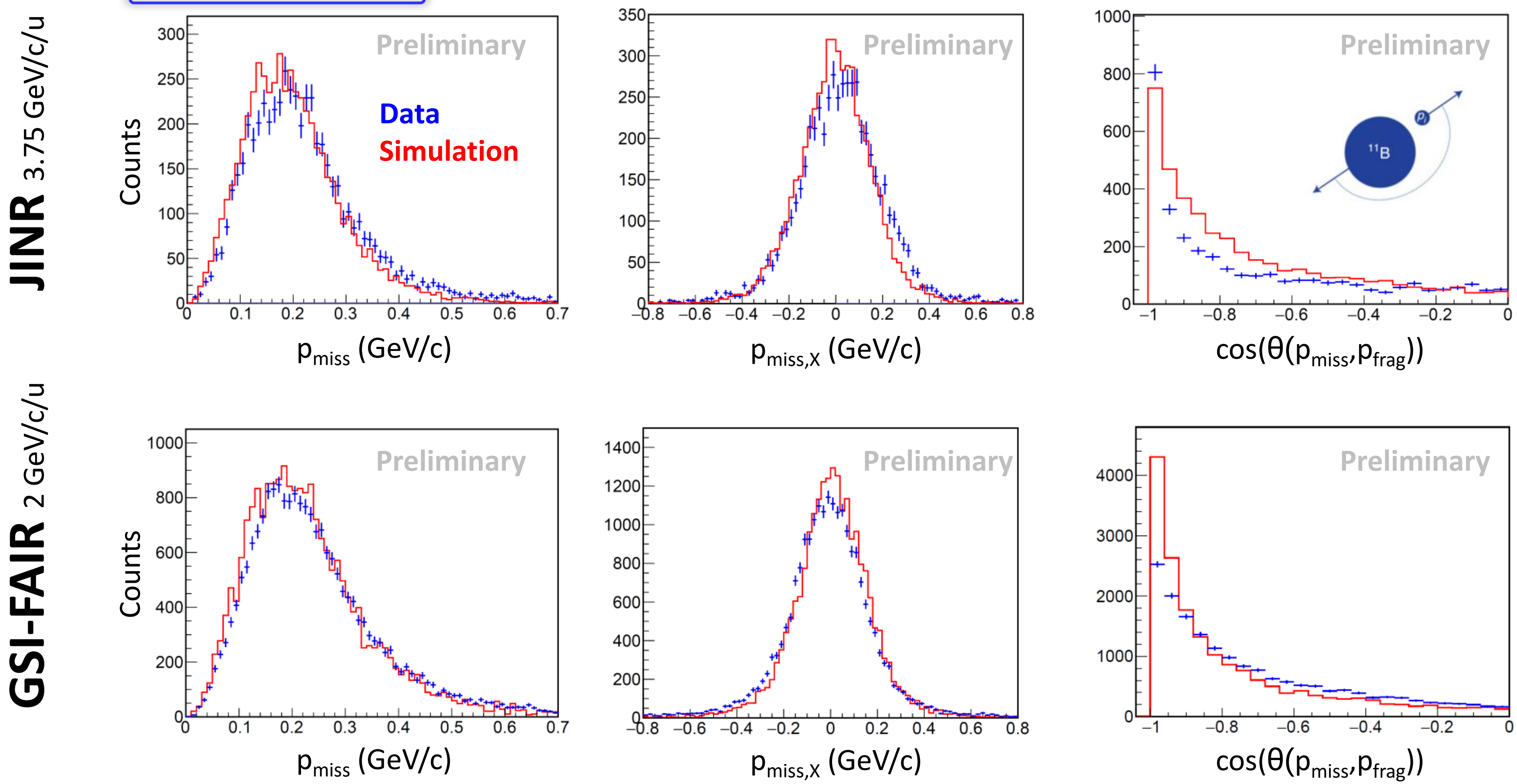
$\boldsymbol{p}_{\text{miss}} = -\boldsymbol{p}_{\text{A-1}}$



M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

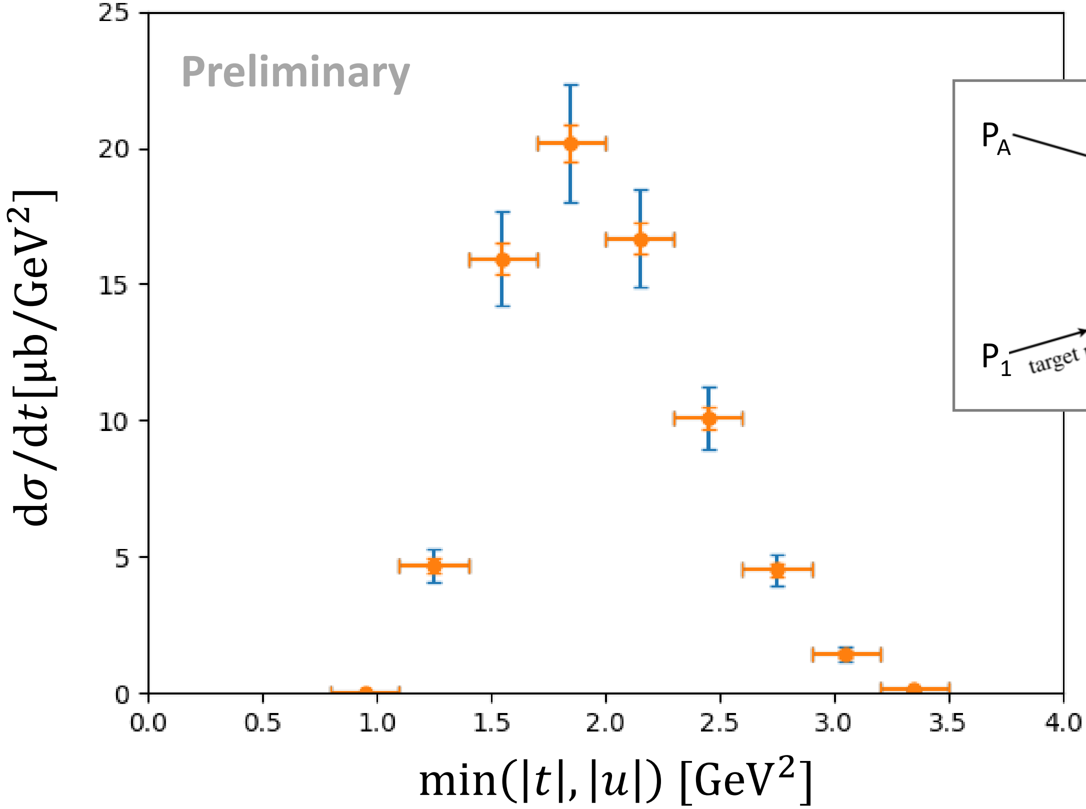
New 2022 data: QE $^{12}C(p,2p)^{11}B$

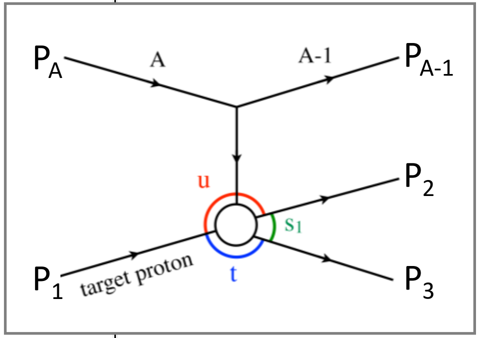
New data: 10x !



QE cross section $^{12}C(p,2p)^{11}B$ at 3.75 GeV/c/u

$$\sigma_{exp} = 22.1 \pm 0.5\ (\text{stat}) \pm 1.6\ (\text{sys})\ \mu\text{b}$$

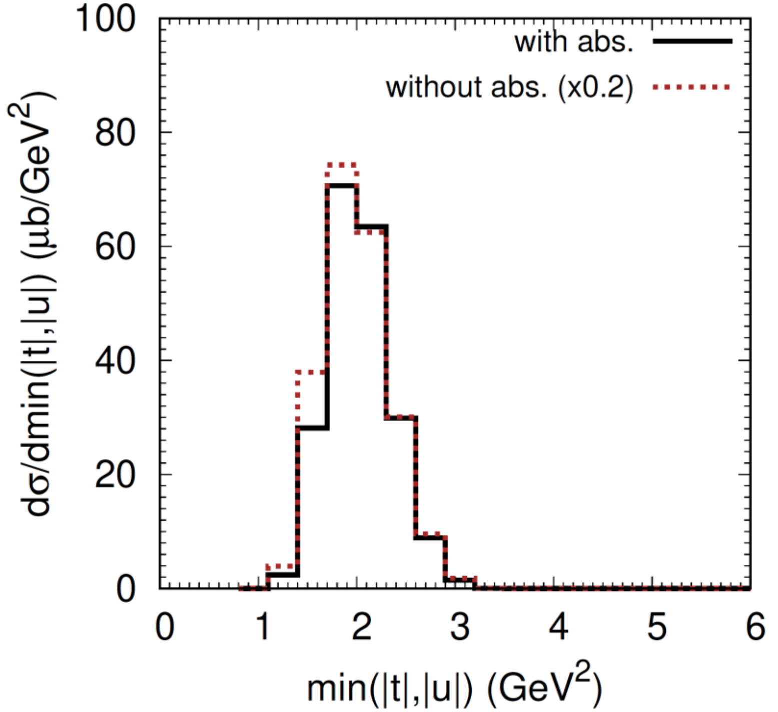




Theory comparison:
Translationally-invariant shell model

σ ~ nuclear structure + reaction [A. Larionov, PRC 110 (2024)]

~ Shell Model [WS + 2-body] **– absorption** [Glauber calculation]



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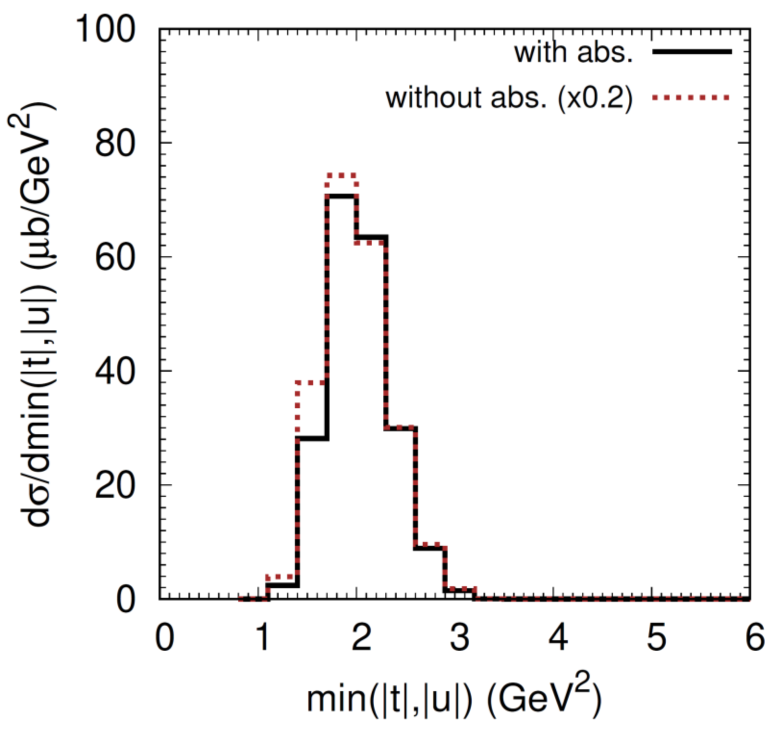
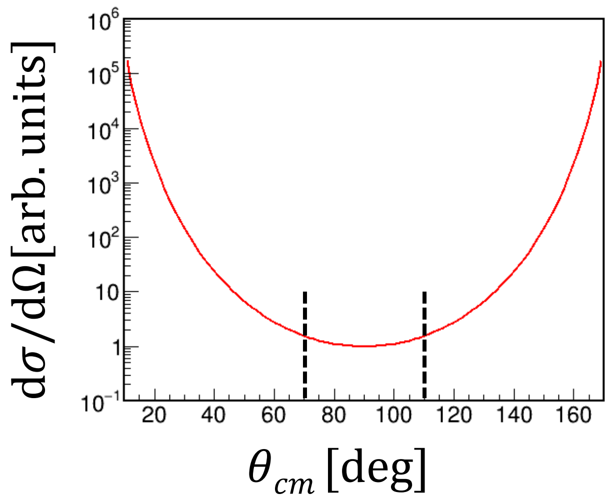
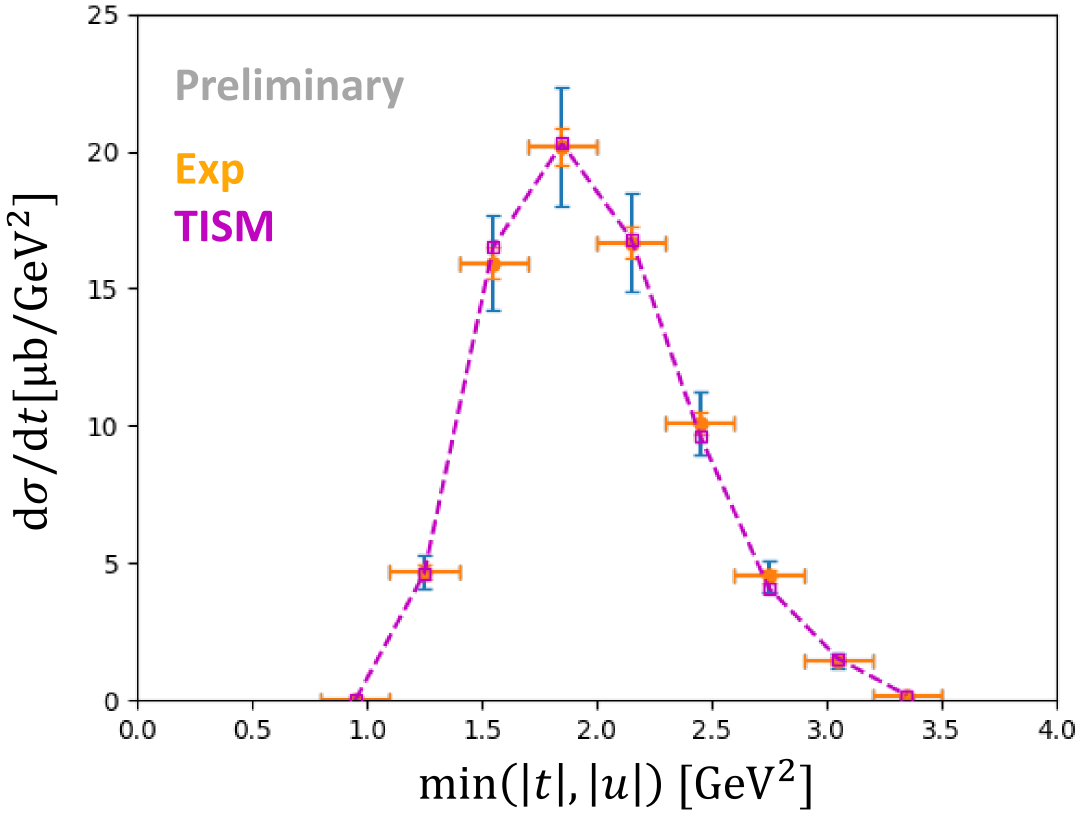


+ Simulation (resolution, acceptance, …)



Preliminary Data-Theory comparison



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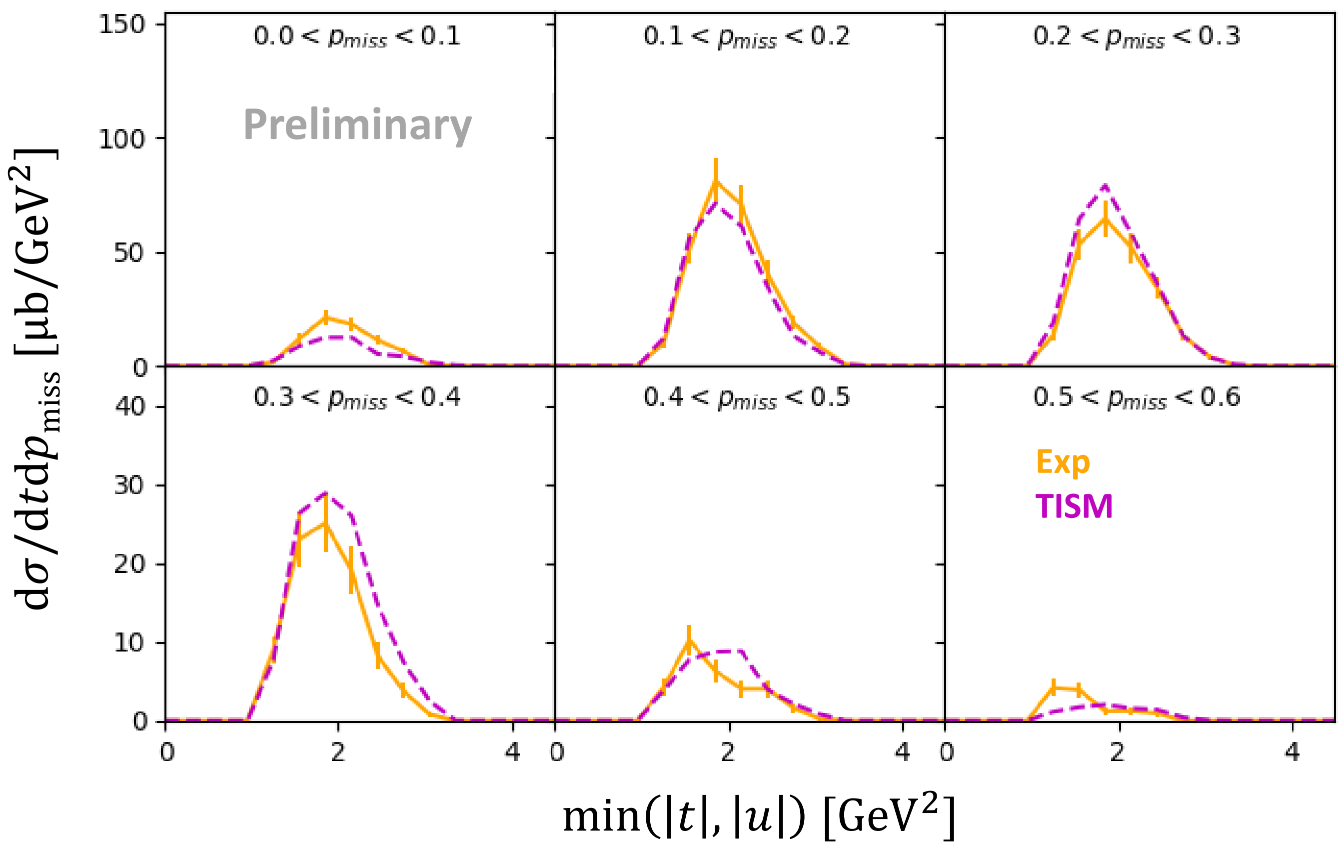


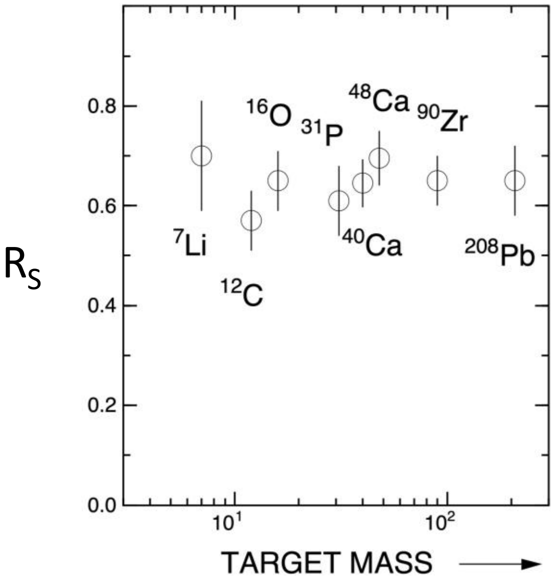
Nuclear structure at high momentum transfer

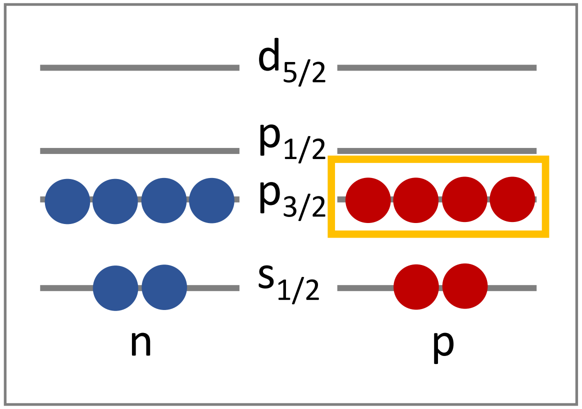
$R_S = \sigma_{exp} \ / \ \sigma_{theo}$

$= 22.1\ \mu b \ / \ 22.5\ \mu b$

$= 0.98 \pm 0.07$

$\neq\ 0.65$ (IPM)

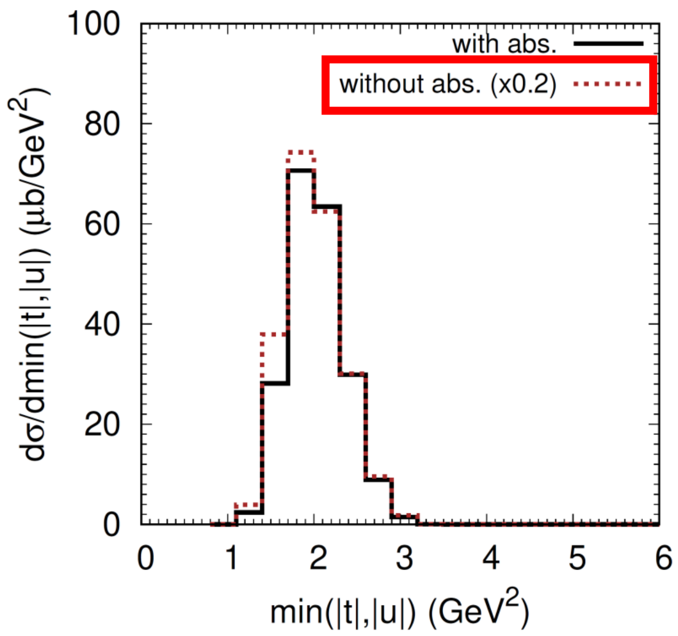




$C^2S = 4.27$
(TISM)

Possible reasons for large R_S

Modified in-medium effects?
High sensitivity to absorption



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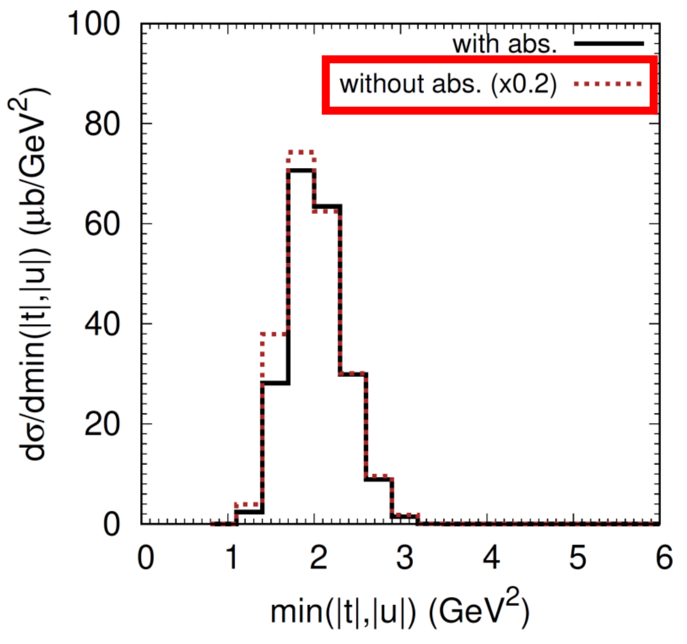
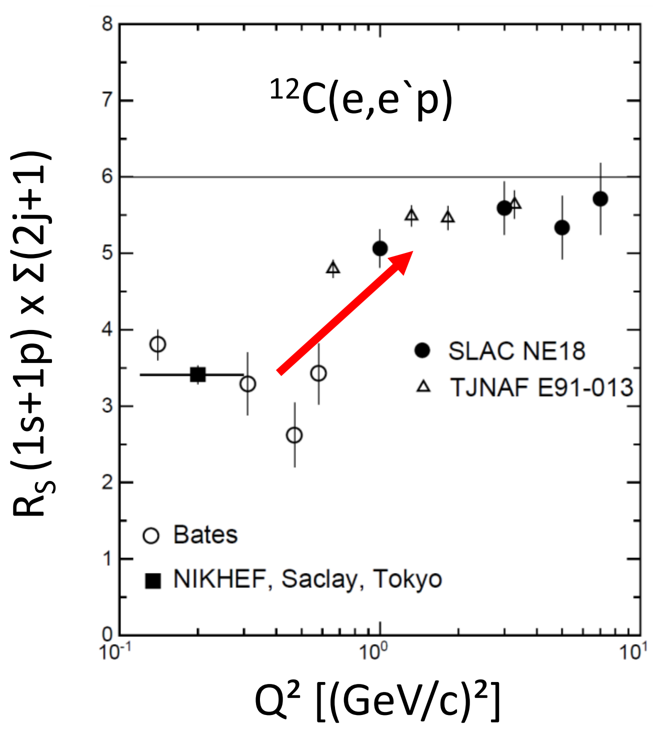


"Unquenching"

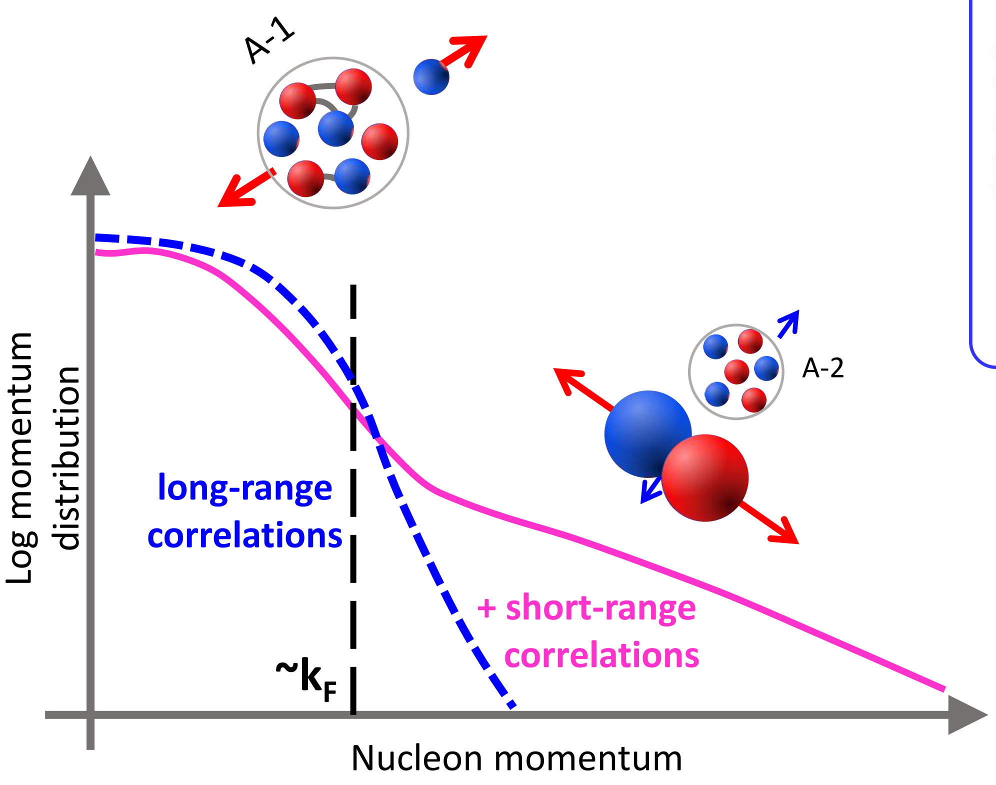


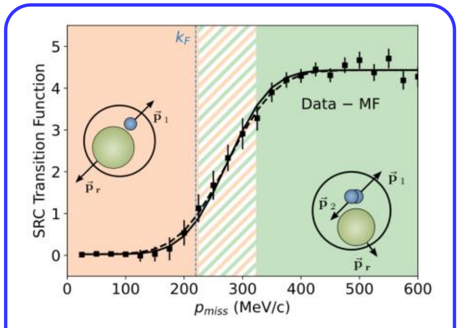
L. Lapikás, G. van der Steenhoven, L. Frankfurt, M. Strikman, M. Zhalov, PRC 61 (2000).

→ Experiment in inverse kinematics

at high energy with hadronic probe

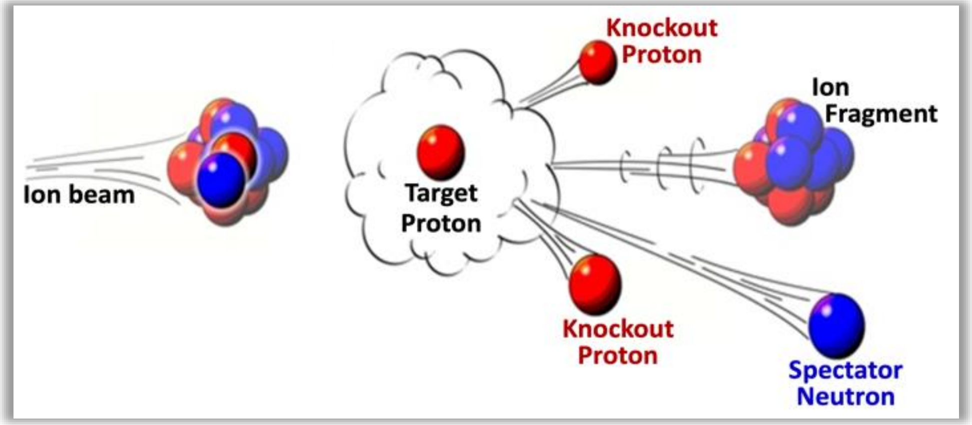
is a “clean” technique to study nuclear structure





→ Mon. talk: Igor Korover

SRC study in inverse kinematics



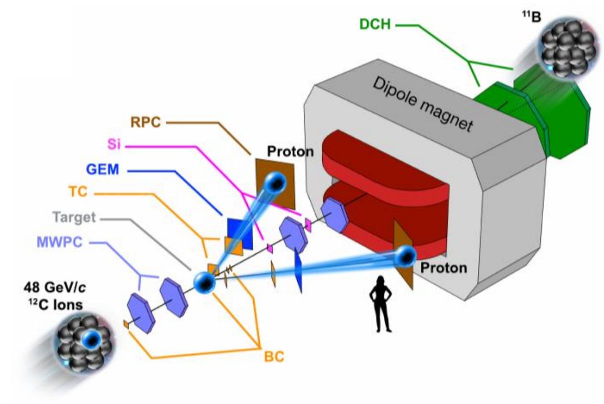
Measure:

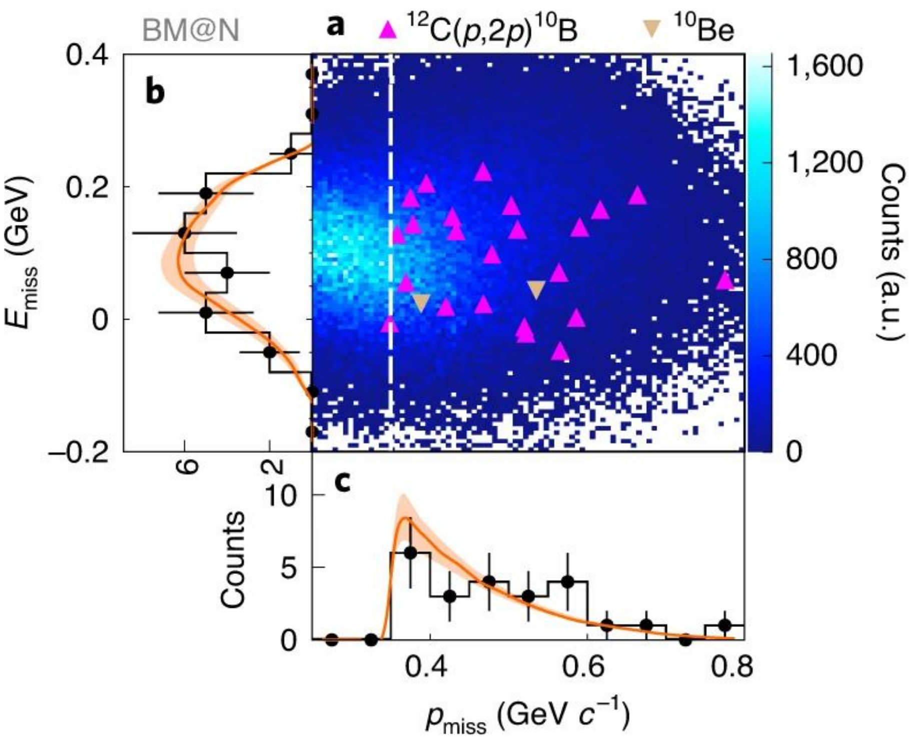
- **scattered proton momenta**
- **fragment momentum**
- **recoil nucleon momentum**
- **final state / energy**

Extract:

p_{miss}
pair c.m.
factorization
pair ratios
spin, parity

JINR 2018:
SRC identification



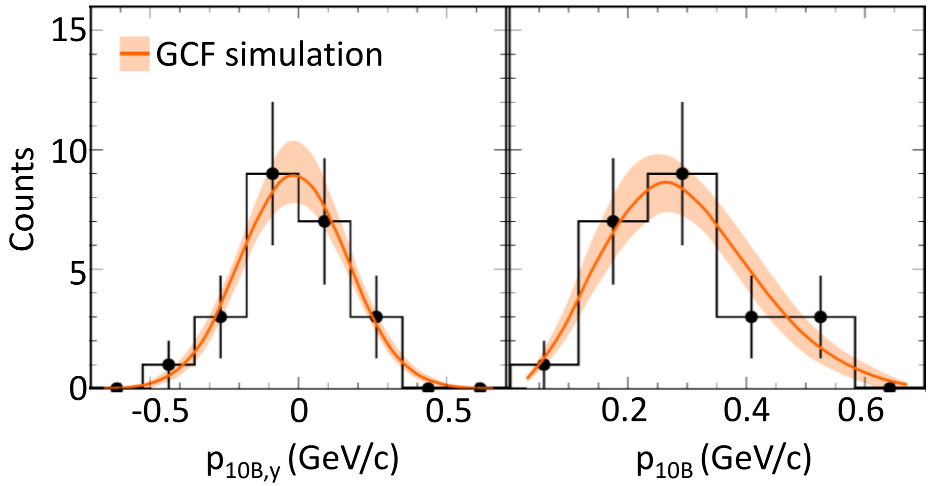


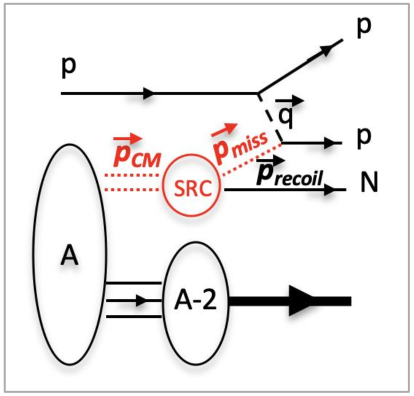
23 *np* pairs (^{10}B)
2 *pp* pairs (^{10}Be)
→ *np* dominance

+ opening angle > 63°, M^2_{miss} > 0.42 (GeV/c²)²,
(guided by GCF)

M. Patsyuk, JK et al. (BM@N), Nat. Phys. 17 (2021).

Fragment momentum = pair c.m. motion

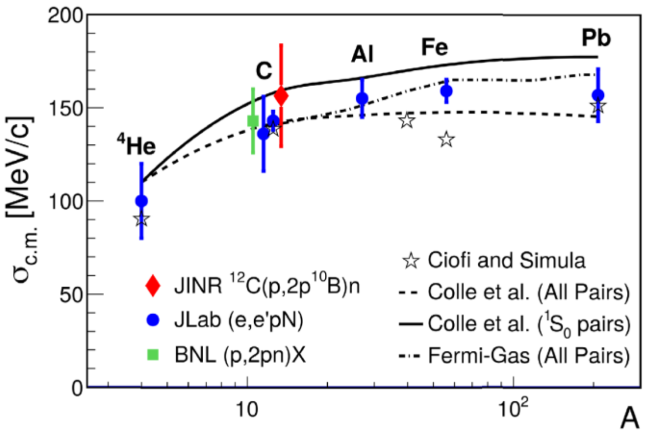




direct extraction:

σ = (156 ± 27) MeV/c

→ small c.m. momentum



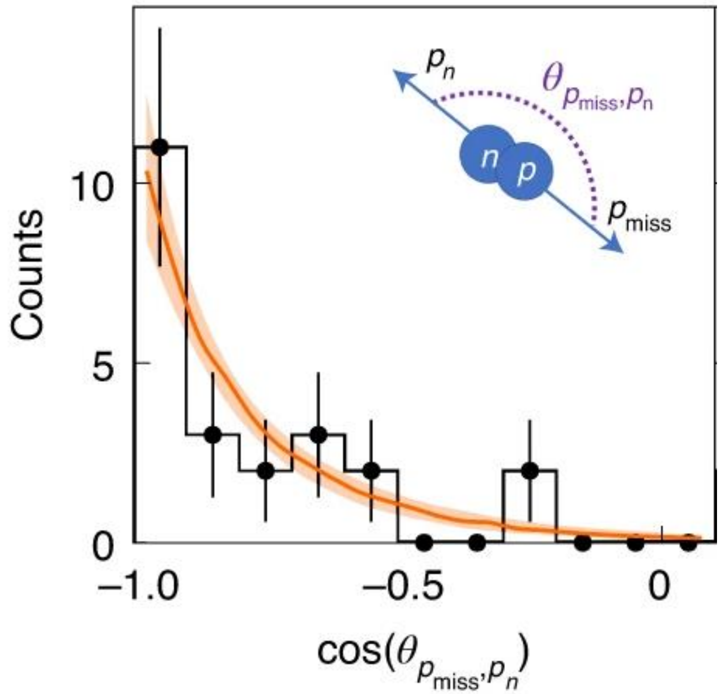
M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

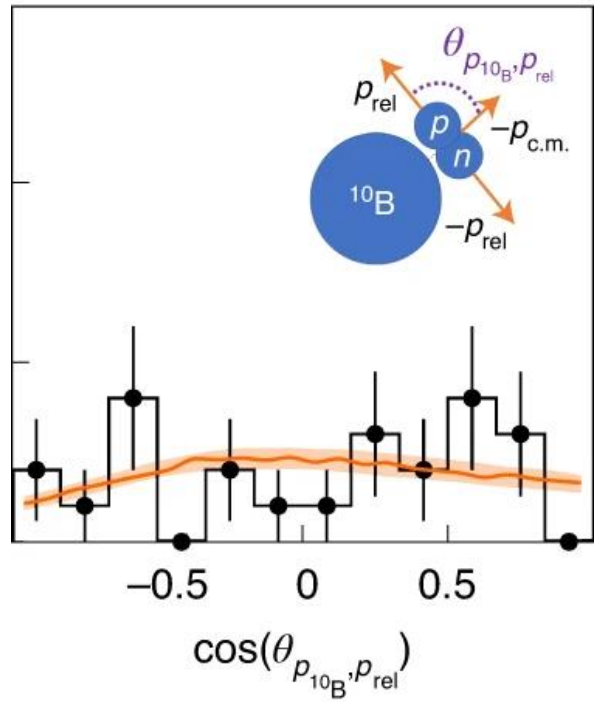
Pair correlations

strongly correlated pair:
NN back-to-back emission

weak interaction between
pair and A-2 spectator

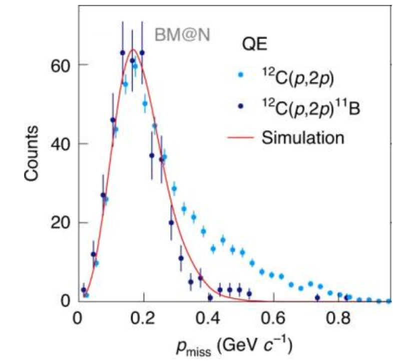
→ **Factorization measured directly**





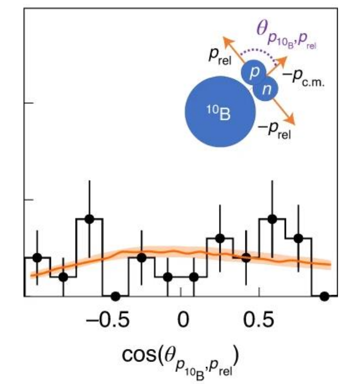
M. Patsyuk, JK et al., Nat. Phys. 17 (2021).

I. **Study nuclear ground-state distributions**
Inverse kinematics (p,2p) reactions at high energy,
suppresses quantum-mechanical interference



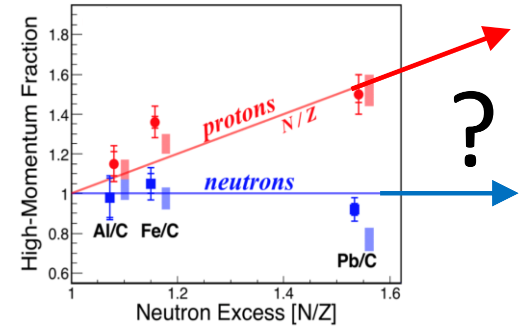
II. **Absorption and spectroscopic strength**
at large momentum transfer

III. **Study of SRCs with hadronic probes**:
1st SRC experiment in inverse kinematics
with access to new observables -> probe universality



IV. **Study of cold dense nuclear matter**:
Pathway for SRC studies with radioactive nuclei

V. **Inverse kinematics with polarized beams**



Thank You.

JINR Experiment

Göran Johansson (TAU)

Timur Atovuallev (JINR)

Sergey Nepochatykh (JINR)

Yaopeng Zhang (Tsinghua U)

Vasilisa Lenivenko (JINR)

GSI-FAIR Experiment

Hang Qi (MIT)

Andrea Lagni (CEA)

Manuel Xarepe (U Lisbon)

Enis Lorenz (TUDa)

Maria Patsyuk, Eli Piasetzky, Zhihong Ye.
Anna Corsi, Or Hen, Tom Aumann, Meytal Duer, Valerii Panin.